Evaluation of Separation Mechanism Design for the Orion/Ares Launch Vehicle

Abstract:

As a part of the preliminary design work being performed for the Orion vehicle, the Orion to Spacecraft Adaptor (SA) separation mechanism was analyzed and sized, with findings presented here. Sizing is based on worst case abort condition as a result of an anomaly driving the launch vehicle engine thrust vector control hard-over causing a severe vehicle pitch over. This worst case scenario occurs just before Upper Stage Main Engine Cut-Off (MECO) when the vehicle is the lightest and the damping effect due to propellant slosh has been reduced to a minimum. To address this scenario and others, two modeling approaches were invoked. The first approach was a detailed 2-D (Simulink) model to quickly assess the Service Module Engine nozzle to SA clearance for a given separation mechanism. The second approach involved the generation of an Automatic Dynamic Analysis of Mechanical Systems (ADAMS) model to assess secondary effects due to mass centers of gravity that were slightly off the vehicle centerline. It also captured any interference between the Solar Arrays and the Spacecraft Adapter. A comparison of modeling results and accuracy are discussed. Most notably, incorporating a larger SA flange diameter allowed for a natural separation of the Orion and its engine nozzle even at relatively large pitch rates minimizing the kickoff force. Advantages and disadvantages of the 2-D model vs. a full 3-D (ADAMS) model are discussed as well.

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Kevin E. Konno, Daniel A. Catalano, Thomas M. Krivanek
NASA John H. Glenn Research Center, Cleveland, Ohio

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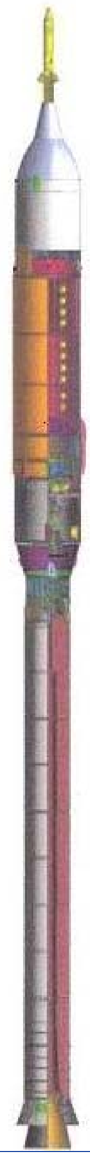
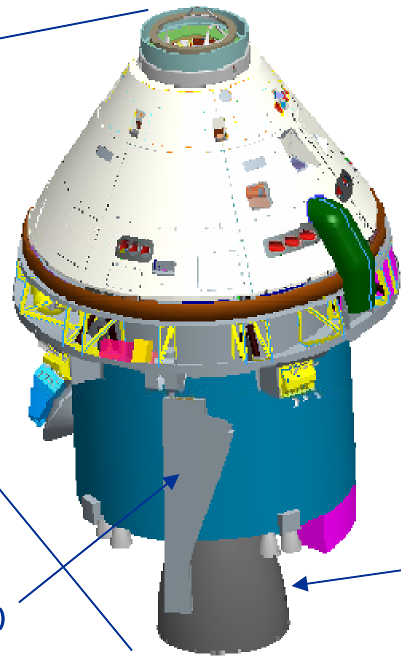
Hardware Overview

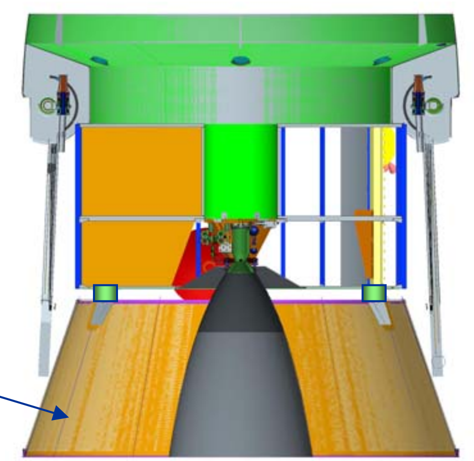


ARES 1 Stack



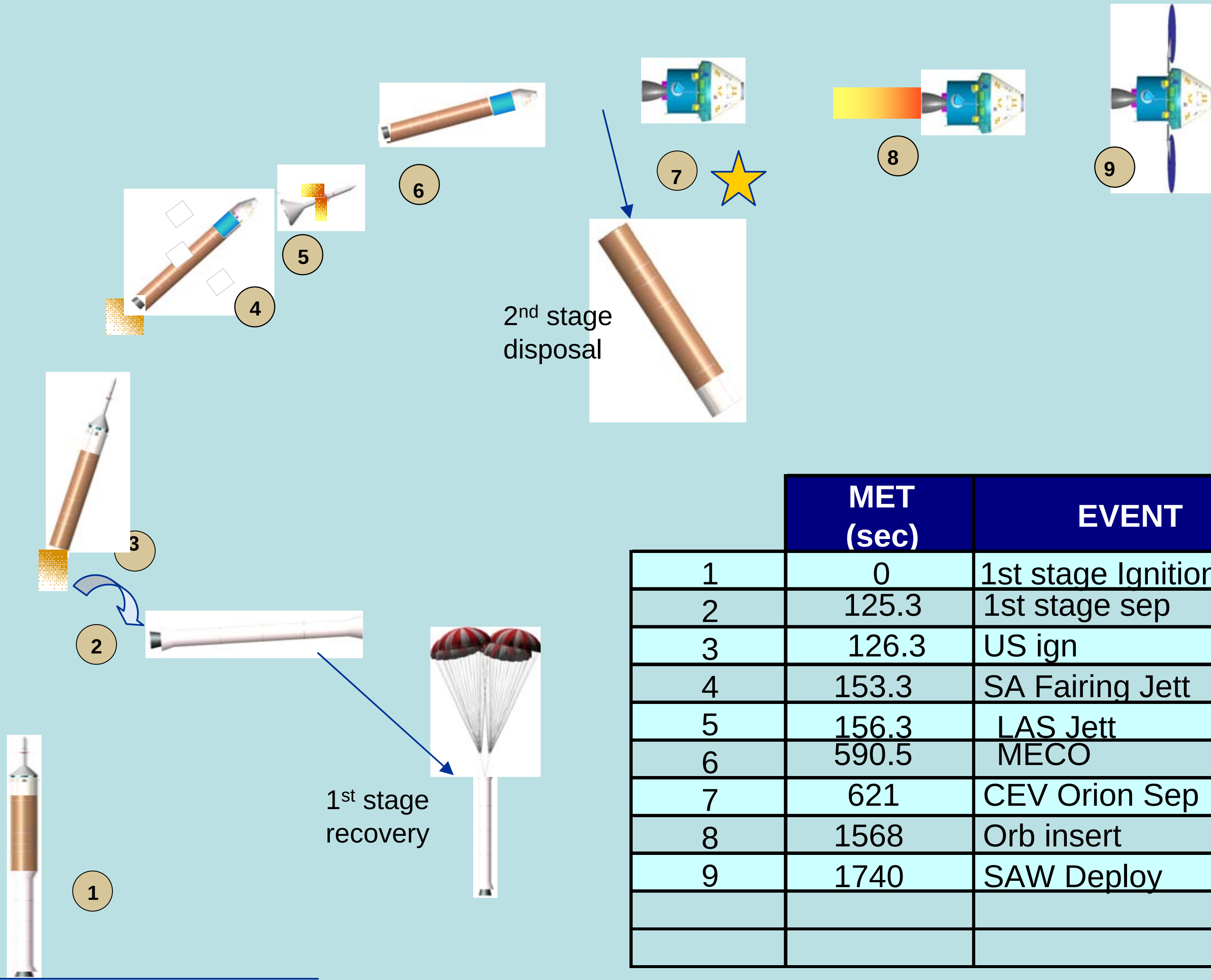
Orion vehicle

(fairings removed)



Service Module (SM)

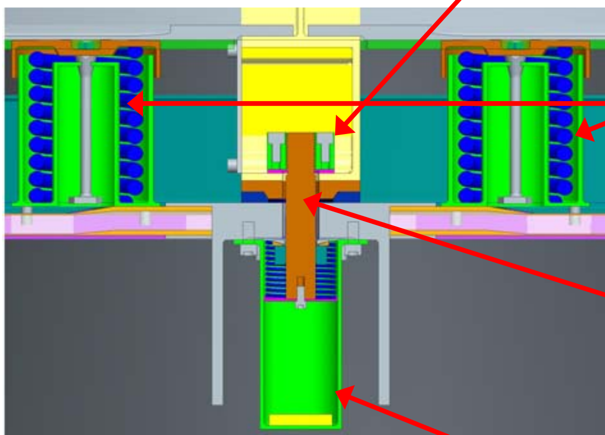
Nominal Ascent Timeline



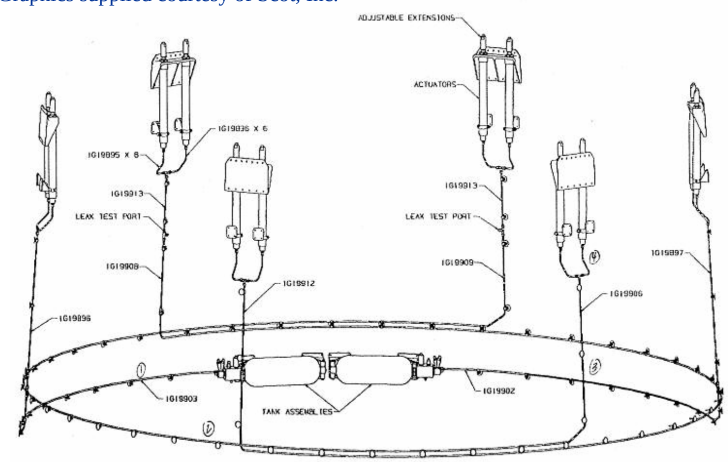
	MET (sec)	EVENT
1	0	1st stage Ignition
2	125.3	1st stage sep
3	126.3	US ign
4	153.3	SA Fairing Jett
5	156.3	LAS Jett
6	590.5	MECO
7	621	CEV Orion Sep
8	1568	Orb insert
9	1740	SAW Deploy

Nominal Separation Event

Separation mechanisms traded:



Graphics supplied courtesy of Scot, Inc.



Compression springs
- •Low part count
- •High reliability
- •Well known
- •simple

Pyrotechnic Gas Thruster
- •Higher specific thrust (~10x springs')
- •Higher part count, possibly lower reliability

Pneumatic actuators
- •Higher specific thrust (~5x springs')
- •Higher part count, possibly lower reliability

From 1983 to 2005, Spacecraft and Fairing separation systems accounted for 10% of all launch failures, according to AAS 03-071 paper. Vehicle dynamics accounted for another 4%.

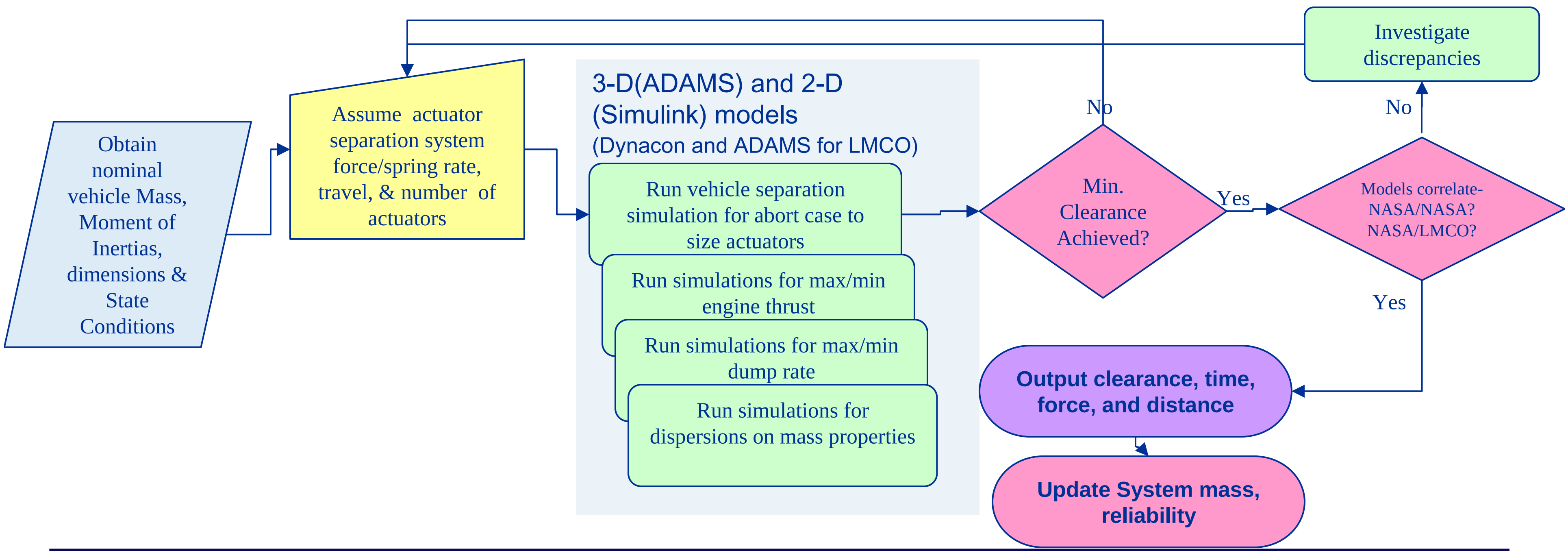
Preliminary Design Process

<u>Design parameters traded/optimized:</u>

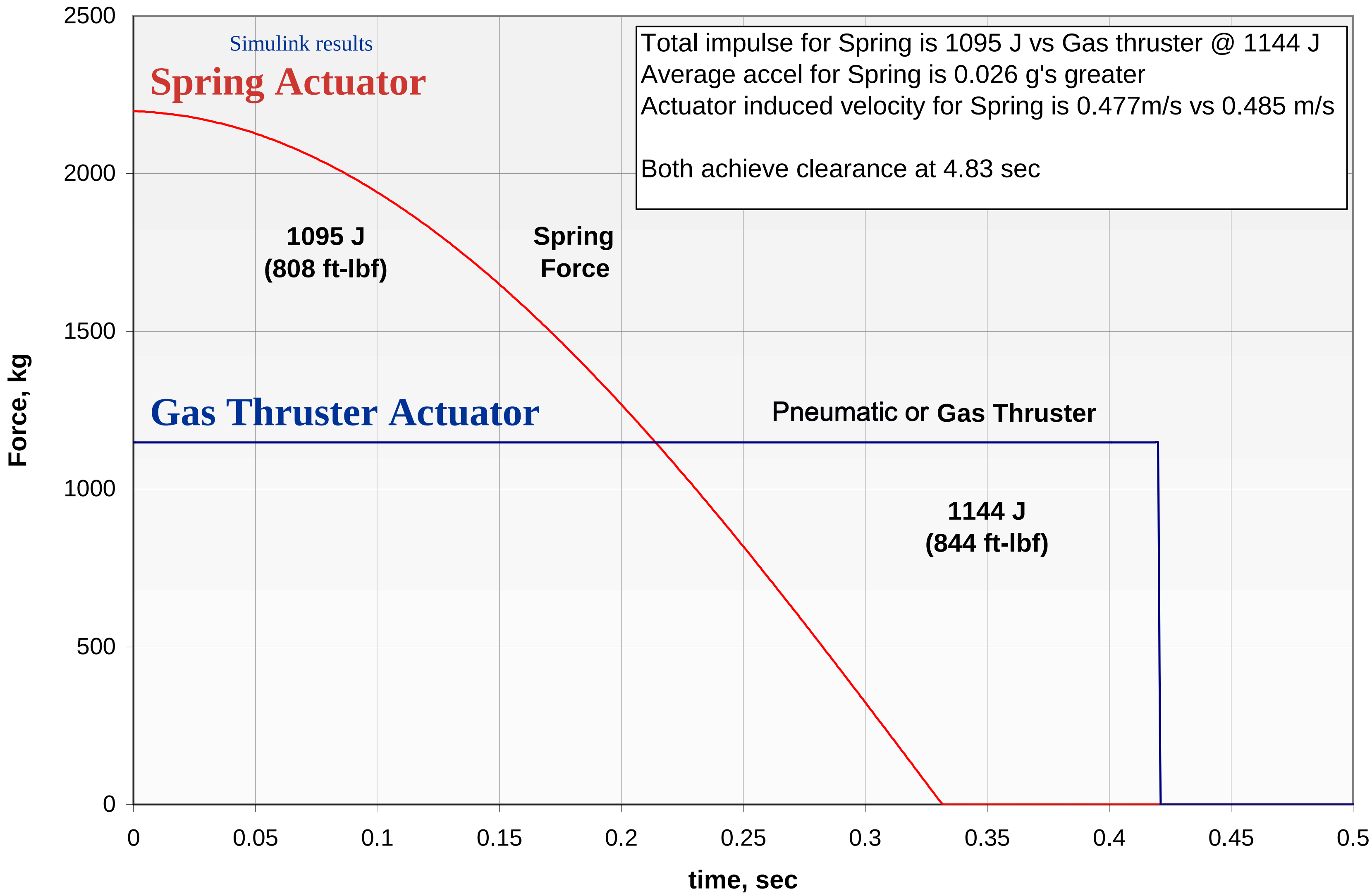
- Actuator type
- Actuator force/stiffness
- Actuator stroke
- Spacecraft Adaptor (SA) flange diameter

<u>Design study variables:</u>

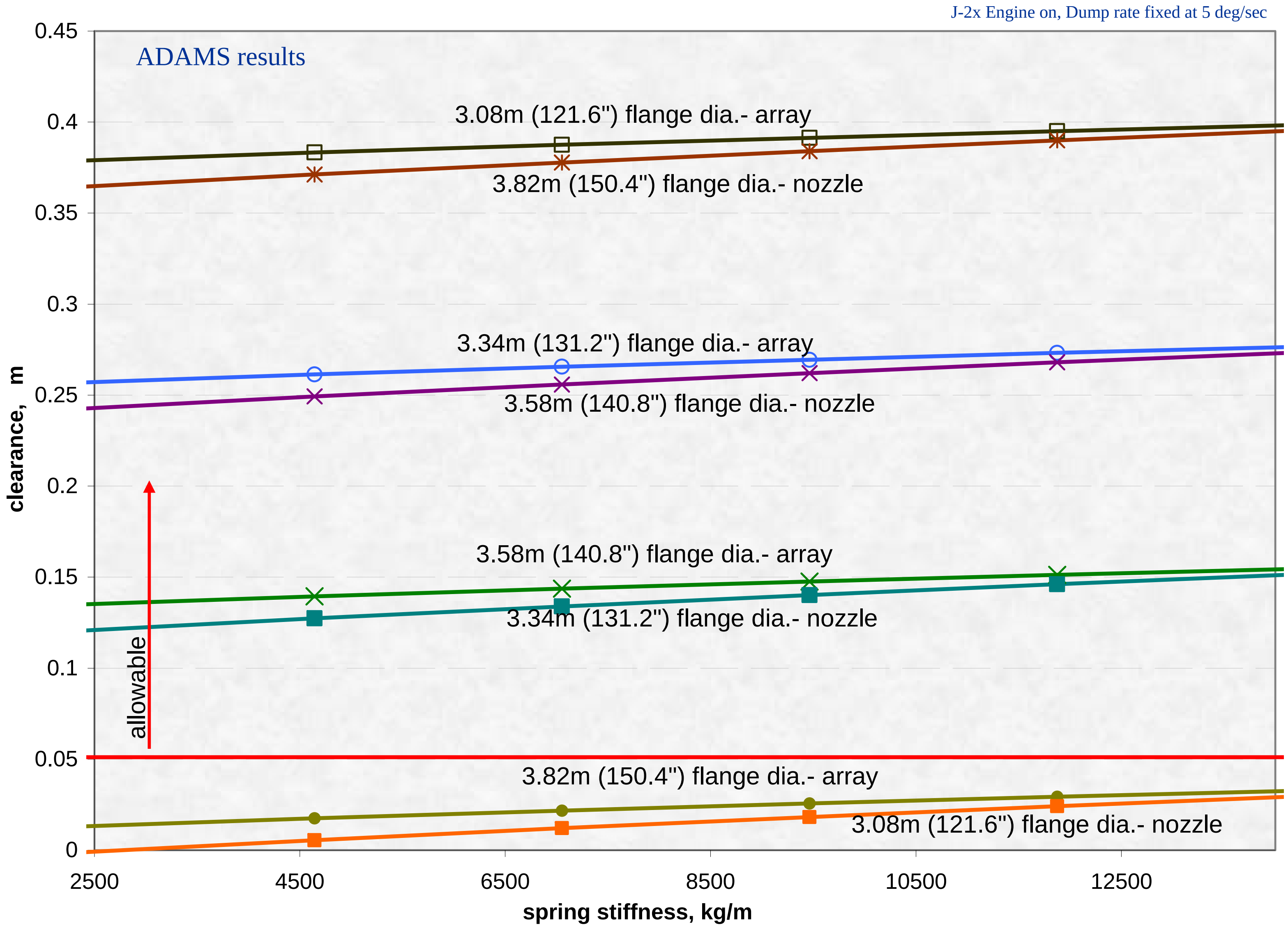
- Upper Stage residual thrust (0 - max lbs)
- Vehicle dump rate & direction (0-35 deg/sec)
- Spring-out condition (1 in 12)
- Vehicle mass property dispersions (+/- 10%)



Characteristics of Force Application

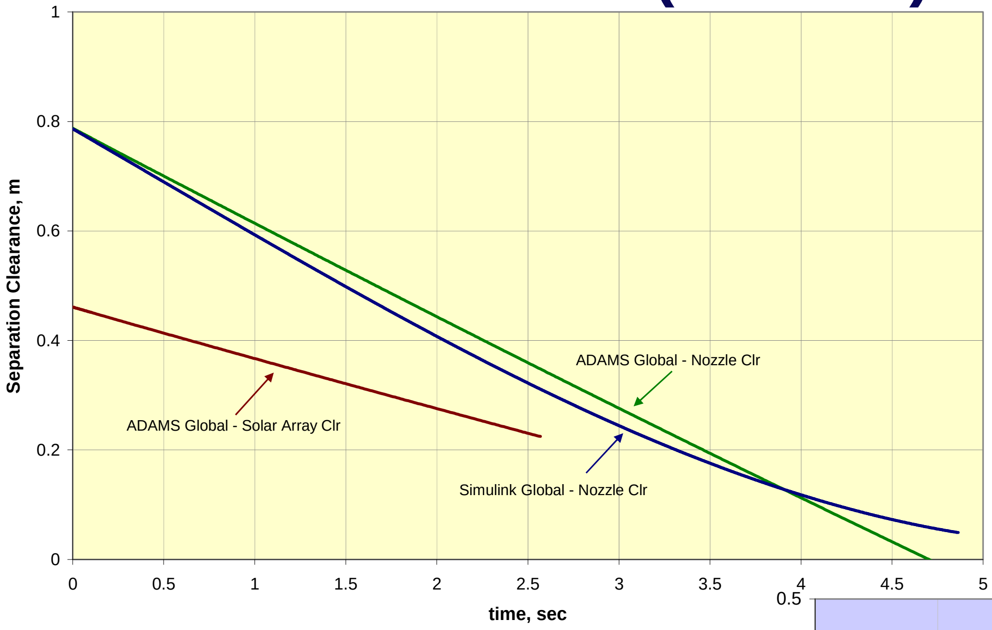


SA Flange Size Optimization
(considering arrays and nozzle clearance)



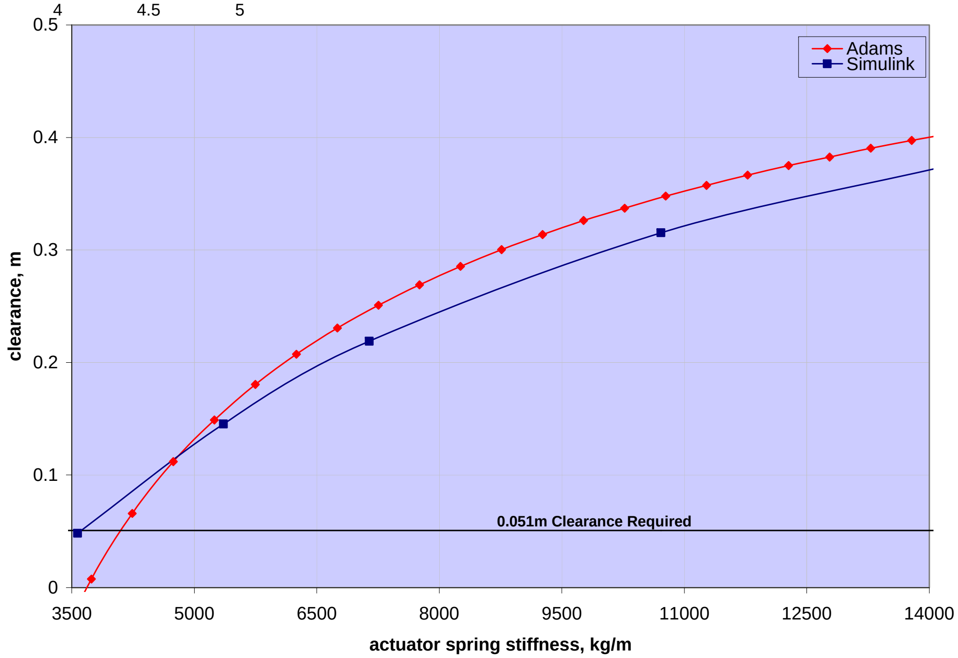
Arrays will clear the SA for any flange diameter smaller than 145”. Engine nozzle will clear SA for any flange diameter larger than 125”.

2-D model vs 3-D (ADAMS) model comparison

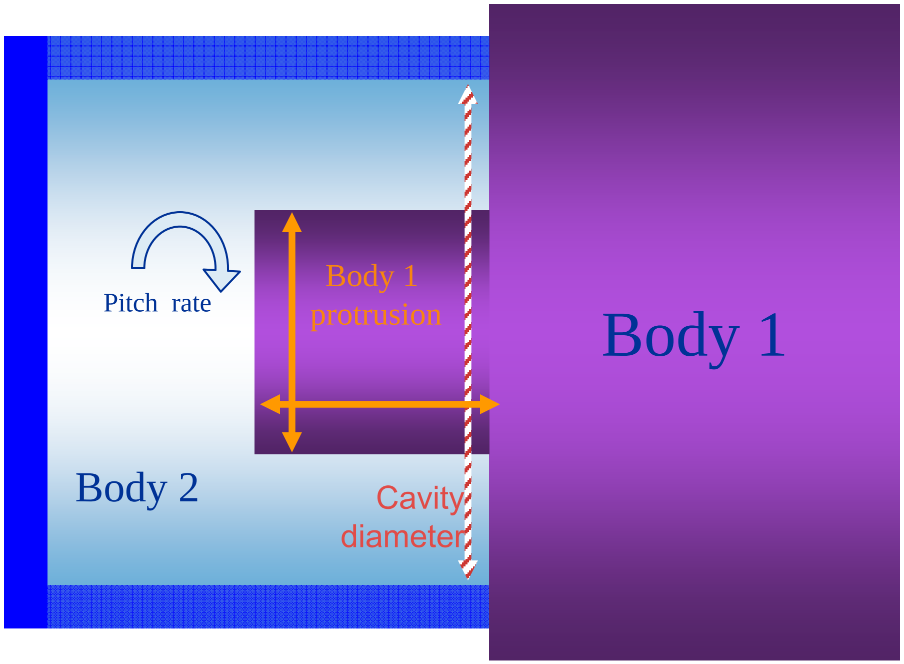


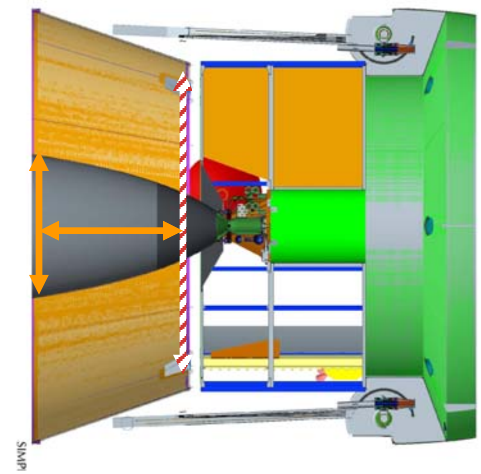
Nozzle clearance vs time curves for a typical design case

Nozzle clearance vs spring stiffness curves for a typical design case



“*Natural Separation*” Concept



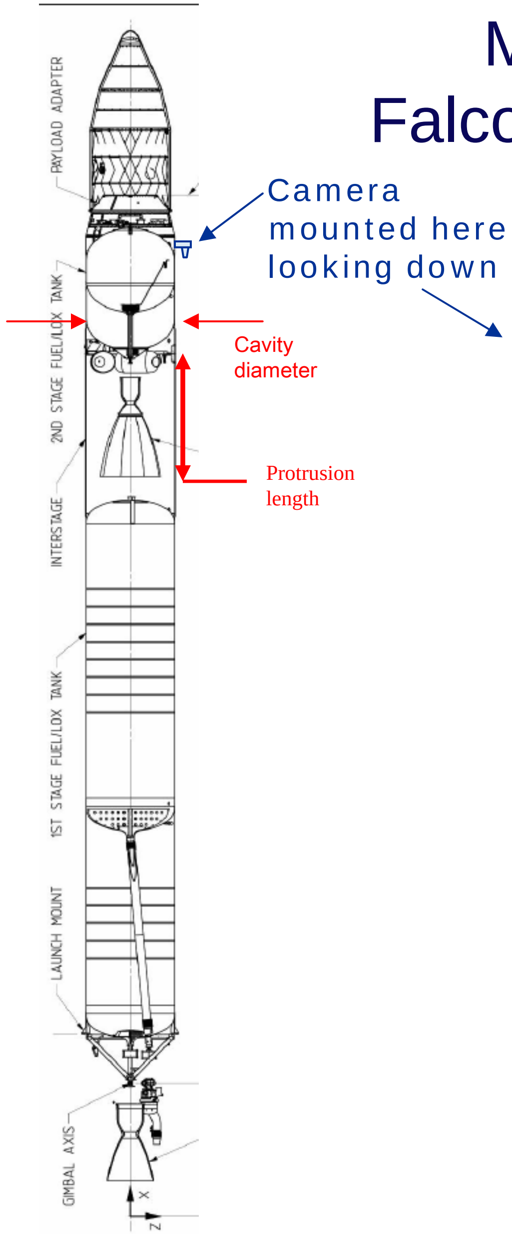


For 2 bodies attached and under constant pitch rate, for a given protrusion diameter and length, upon separation:

- There exists a cavity diameter D that the protrusion will naturally clear at, *regardless of pitch rate*.
- The bodies will separate and protrusion will clear body 2 at a prescribed angular rotation regardless of pitch rate

This neglects outside forces acting on the bodies, which can easily be considered later in design process

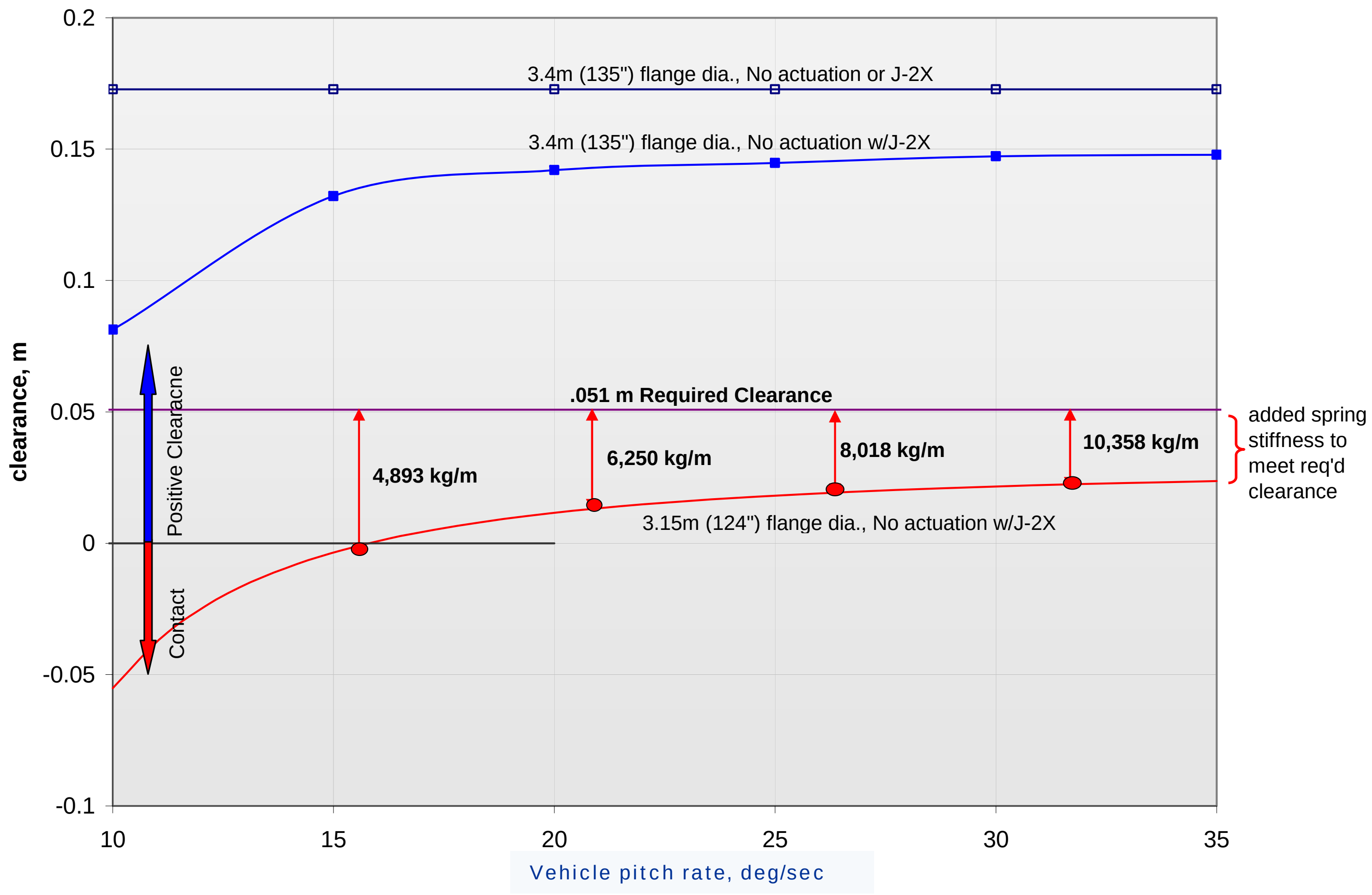
Making use of *Natural Separation*
Falcon 1 Demo Launch- Staging anomaly



Falcon 1 stack

*All information borrowed from SpaceX public website: www.spacex.com

Orion *Natural Separation* Dynamics Benefits At Work



Recontact at Low Dump Rate

Lessons Learned

- For two bodies joined and tumbling at a constant angular velocity, when separated will each maintain that same angular velocity after separation (neglecting outside forces)
- For spacecraft mechanism design sizing, the abort/off-nominal case is not always the driving design case
- Independent analysis and verification of critical vehicle dynamics can be beneficial in avoiding costly corrections later
- Intelligent preliminary sizing of spacecraft separation mechanism geometry sensitive to separation dynamics can improve overall mission reliability and save on mechanism weight, especially if *Natural Separation* concepts are invoked early the design

Conclusions

- Lower fidelity, 2-D equations of motion model can be very useful in separation mechanism design. It provides insight into separation events and the many parameters and their relative sensitivities.

- A more detailed 3-D geometric dynamics model is helpful in considering out of plane effects which may be significant such as CG offsets, single actuator/spring failures, and product of inertia terms.

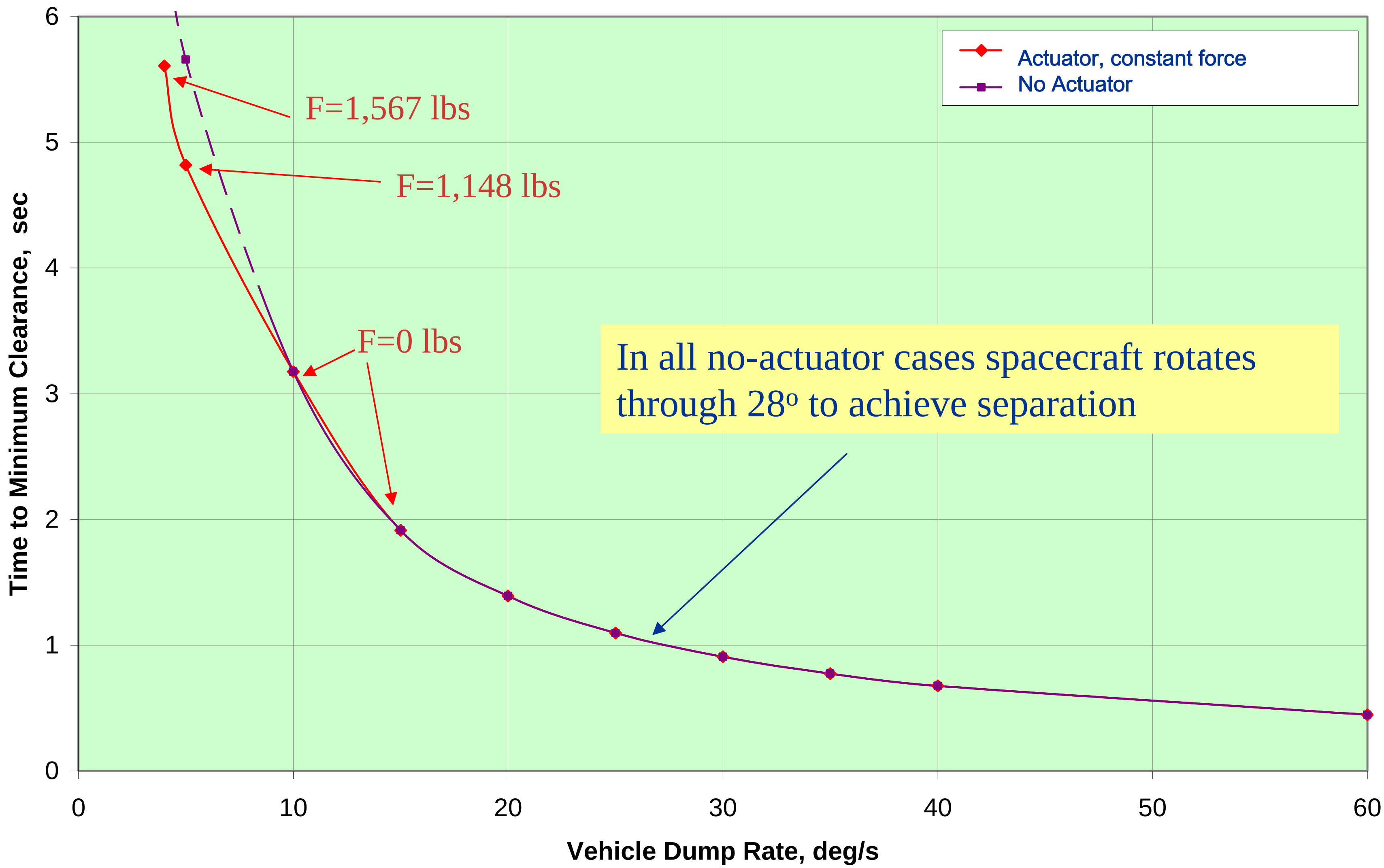
- For the Orion crewed vehicle separation system a simple mechanical spring mechanism has been chosen as the baseline design because the spacecraft geometry was sized efficiently, minimizing the required actuator force even with significant force margin (25%) applied.

Acknowledgments

The authors would like to acknowledge the contributions, advice, and suggestions of Keith Schlagel and Lance Lininger of Lockheed Martin Corporation which aided in the development and compilation of this work.

Further information: Restricted NASA TM *Spacecraft Separation System Dynamics for the Orion/Ares launch Vehicle.* To include vehicle mass properties, full Simulink code, tank slosh modeling.

Backup slides



Time to Minimum Clearance, sec
Vehicle Dump Rate, deg/s
0
1
2
3
4
5
6
0
10
20
30
40
50
60
Actuator, constant force
No Actuator
F=1,567 lbs
F=1,148 lbs
F=0 lbs
In all no-actuator cases spacecraft rotates through 28º to achieve separation

Simulink Flowchart